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LARGE-AREA DEPOSITION FOR CRYSTALLINE SILICON ON GLASS MODULES

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ABSTRACT

This paper presents the current status of the Crystalline Silicon on Glass (CSG) technology for low-cost photovoltaic modules that is being developed at Pacific Solar. This technology combines the low manufacturing cost of large-area monolithic construction with the established durability of crystalline silicon. The heart of the manufacturing sequence for this technology is the PECVD silicon deposition process. Equipment developed for the flat-panel display industry appears to meet the requirements for this process. A single-chamber KAI-800 system from Unaxis has been installed at Pacific Solar that deposits silicon layers onto 0.7-m^2 sheets of textured glass. Initial results using this equipment are reported, including data for deposition rate, uniformity, manufacturing cost, and the performance of small modules made using material deposited in this system.

1. INTRODUCTION

The emergence in this decade of crystalline silicon as the dominant material for photovoltaic modules in a rapidly growing market driven by installation of grid-connected systems comes as no surprise for those who have been actively involved with this technology [1].

However, even the most cost-effective residential rooftop photovoltaic systems are not yet able to compete on a life-cycle cost basis without subsidy against utility electricity provided from conventional sources. To do so requires a technology that combines low module cost ($\$/W_{dc}$), low system installation cost ($\$/W_{ac}$), excellent durability (¢/kWh), and widespread market acceptance. It doesn't do any good to exceed the requirements in one or two of these areas if there are deficiencies in any of the others.

Thin-film technologies have historically focused on reducing module cost, but frequently without sufficient regard for the other considerations. Wafer-based crystalline silicon modules do well in terms of durability and market acceptance, but require massive investments in huge factories to drive the cost down. At Pacific Solar, Crystalline Silicon on Glass has been developed from the outset using a balanced approach that is designed to meet all of these criteria simultaneously [2,3].

2. CSG TECHNOLOGY

The CSG structure that has given the best efficiencies to date is illustrated in Fig. 1. A 660-cm^2 module using this design was measured outdoors at Sandia National Labs in July 2002 and found to have an aperture-area efficiency of 8.2% [4].

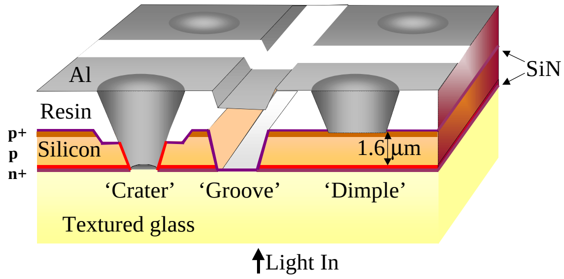

Fig. 1 Key features of CSG technology (not to scale).

Low-iron float glass is textured, then coated using PECVD with a layer of silicon nitride and 1.6 µm of silicon using an n^+pp^+ structure. The amorphous silicon layer is then crystallised in a thermal process followed by hydrogen passivation. A laser is used to slice the layer of silicon into individual cells and a mask pattern is used to remove the p^+ layer from the vicinity of the n-type crater contacts. A thin cap layer of silicon nitride is deposited followed by a few microns of low-cost resin. Openings are made though the resin and cap nitride to allow the aluminum metal to contact the p^+ surface at 'dimples' and the buried n^+ layer at 'craters'. The metal is then scribed using a laser to create an interdigitated contacting pattern that monolithically interconnects the adjacent cells in series. This contacting scheme leaves 99% of the silicon area active for photogeneration.

Two thousand modules have been produced on the research pilot line that was established at Pacific Solar's headquarters in the Sydney suburb of Botany in 1998. Some of these modules have been used to fabricate a grid-connected PV system located on the roof over the pilot line, as illustrated in Fig. 2. This and two more planned installations off-site are being supported by a cost-shared grant from the Australian Greenhouse Office.

Fig. 2. Grid-connected CSG system mounted on the roof of Pacific Solar's pilot line in Sydney.

3. CSG MANUFACTURING

Analysis indicates that 8% efficiency is adequate for CSG technology to meet all of the criteria for success mentioned in the Introduction if it can be obtained for large modules more than 1.2 m^2 in size. Having achieved this efficiency milestone, attention was turned to tackling the issues associated with scaling up the technology for manufacturing, both in terms of increased glass size and reduced cycle times for the critical processes.

The manufacturing sequence required to implement the CSG structure is illustrated in Fig. 3. This diagram shows each item of equipment required for a factory with a capacity of 20 MW/yr at 8% efficiency. The fact that enough is known now about this technology to be able to specify the type and number of machines needed for factory production is testament to the fact that no more scientific breakthroughs are required; all that's needed is an engineering effort to work out the details.

The processes fall into four sectors. At lower right is Glass Preparation. This is followed by Silicon Preparation, which includes silicon deposition, crystallisation, defect anneal and hydrogen passivation. Batch processing is used for deposition and crystallization, but the rest of the sequence is performed in-line, at a rate of one sheet every 2.5 minutes. At the top is Device Fabrication, where contacts are made to the n^+ and p^+ layers and the metal is scribed to monolithically interconnect the adjacent cells in series. The rest is Module Assembly, where a second sheet of glass is laminated to the rear of the superstrate glass to encapsulate the active layers. Contacts are made through holes in this backsheet, resulting in a completed laminate.

4. LARGE-AREA DEPOSITION

The factory layout shown in Fig. 3 is based around two KAI-1200 deposition machines made by Unaxis Balzers. These machines were developed for the flat-panel display industry, but they suit the requirements for photovoltaic manufacturing quite well. Each machine has twenty chambers that operate in parallel.

In 2002, Pacific Solar purchased a single-chamber version of the Unaxis KAI-800 deposition machine and installed it in the pilot line. This is a half-sized version of the KAI-1200 planned for factory production. It processes glass sheets with an area of about 0.7 m^2 but is otherwise identical in design. Using this machine, a deposition process can be developed knowing that only minor modifications will be required to get the same results using a 20-chamber KAI-1200 in a factory. Fig 4 shows the system installed at Pacific Solar. The load lock is in the foreground and to its left is the deposition chamber.

Fig. 4. Single-chamber KAI-800 at Pacific Solar.

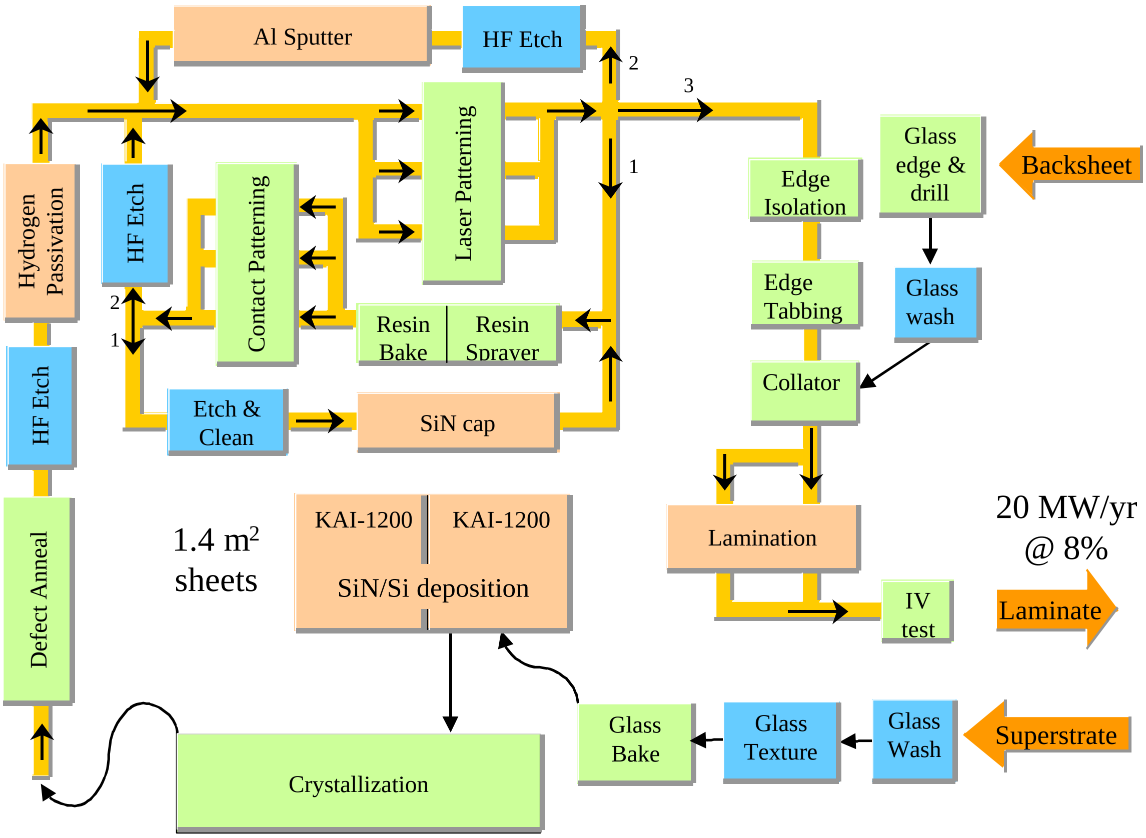

Fig. 3. Proposed factory flow for 20 MW/yr CSG production.

A major benefit of working with equipment that was developed for flat-panel displays is that the equipment issues that usually plague thin-film efforts have already been worked out to a significant degree. For example, Fig. 5 is a plot showing the thickness uniformity obtained over a KAI-800 glass sheet for silicon deposited at the rate of 45 nm/minute, which is the deposition rate currently used for modules produced in the pilot line.

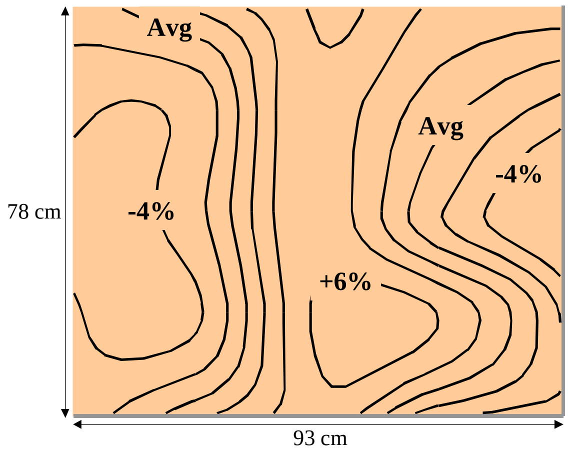

Fig. 5. KAI silicon thickness uniformity.

At a deposition rate of 45 nm/min, the KAI can deposit the CSG structure and clean the chamber *in situ* in preparation for the next deposition in 86 minutes. Table I shows how this cycle time is divided between the various steps in the process as currently practiced at Pacific Solar.

Table I. Components of the cycle time for 1.6-µm silicon deposition at 45 nm/min.

Step	**Time (minutes)**
Load glass	1
Heat glass	10
SiN deposit	2
Pump/purge	10
Si deposit	36
SiO_2 deposit	3
Pump/purge	1
Unload glass	1
Plasma clean	20
Pump/purge	2
TOTAL	**86**

The gases required for both the deposition and cleaning portions of the process are listed in Table II, normalized to the area of the glass sheet.

Table II. Gas feedstock for 1.6-µm CSG deposition.

Material	**Amount Used**
SiH_4	32 g/m^2
SF_6	216 g/m^2
N_2O	15 g/m^2
NH_3	2 g/m^2
N_2	625 L/m^2
H_2	10 L/m^2
O_2	6 L/m^2

The cost of the gases required for this process is about US\$10/m^2. A twenty-chamber KAI-1200 operating in a factory environment should have the same cycle time as that listed in Table I. Assuming a 90% uptime for the equipment, the depreciation of the machine over a ten-year period adds an additional US\$10/m^2 to the manufacturing cost. Other lesser costs would be for labor (US\$1/m^2), and facility operation and maintenance (US\$5/m^2), giving a total manufacturing cost for the silicon deposition of US\$26/m^2. This represents about 20% of the total manufacturing cost for CSG panels based on the current process used in the pilot line.

The pilot line is not yet able to process the large-area sheets through the device fabrication steps. Instead, the sheets are cut into smaller pieces that can be processed using the available equipment. Fig. 6 shows the progress that has been made in the performance of these small modules made using material deposited in the KAI. When the KAI was first installed in 2002, the best efficiency obtained was about four and a half percent. By working through the issues one by one, steady progress is being made. The rate of progress is good and improvement is expected to continue until the 8% efficiency obtained using the smaller-area deposition system is met or exceeded, presumably later in 2003.

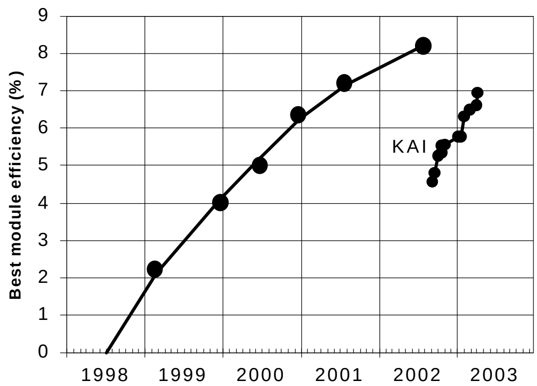

Fig. 6. Efficiency of the best modules using material deposited over large areas in the KAI, compared to previous results for smaller-area depositions.

Small modules have been made from material selected from various locations within the KAI-sized sheets to test the uniformity of the silicon quality. The uniformity of the performance is quite good. One set of modules included samples cut from along an outer edge and from a corner of the large-area sheet. The range of power output was just ±3% relative to the average.

5. CSG DURABILITY

While the efficiency of CSG modules is thought to be adequate, the durability of these modules sets them apart from all other thin films. Since the early days of pilot production, small pilot-sized modules have been mounted on the roof for continuous outdoor exposure. These are visible in the lower-left corner of Fig. 2. The modules are taken down periodically for a brief period to measure their performance using an indoor flash simulator. As illustrated in Fig. 7, there has been no degradation in the output of any of these modules.

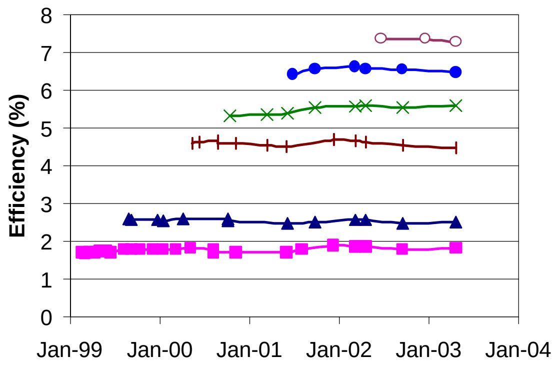

Fig. 7. Stable performance of small CSG modules exposed outdoors in Sydney for periods ranging from one to four years.

In accelerated testing, CSG modules appear to be even better than the wafer-based crystalline silicon modules that are the workhorse of the current PV industry.

We have developed a 'combined cycle' durability test sequence that causes significant degradation even in high-quality wafer-based crystalline silicon modules. This test is much more severe than standard qualification testing, which requires modules to survive temperature cycling, humidity-freeze, or damp heat. The combined cycle test subjects the *same* module to all three of these tests in succession. If a module survives the first cycle, the test is repeated until the module has degraded by 20% or more. Once a module drops to less than 80% of its initial power, linear interpolation is used to estimate when during its last cycle it reached the 80% point, hence the time to reach 20% degradation usually includes some fraction of a cycle.

Fig. 8 illustrates the results of combined-cycle testing of both the CSG technology and some major brands of photovoltaic modules. A pair of commercial CIS modules were also tested, for comparison. The CIS modules were measured outdoors rather than under pulsed illumination due to capacitive contact effects that developed early in the testing sequence.

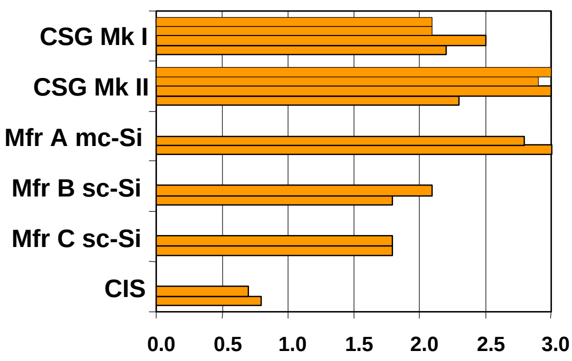

Fig. 8. Number of combined cycles required to degrade module performance by 20% for two versions of CSG technology and four modules from major manufacturers.

Two different versions of the CSG technology survived more than two of these combined cycles, whereas the same can be said for only only one of three major brands of crystalline-silicon modules that we tested. All of these commercial modules have passed standard qualification testing. The combined-cycle test appears to offer a better measure of real-world durability.

6. CONCLUSION

Crystalline Silicon on Glass has been designed from the outset to address all of the issues that must be satisfied for photovoltaics to have a significant impact on global electricity production. It does this by combining the low-cost features of thin-film approaches with the durability of crystalline silicon.

Just as photovoltaic technology based on silicon wafers has always relied heavily on equipment developed for the integrated circuit industry, CSG is able to use equipment that has been developed for the flat panel display industry. Equipment that deposits silicon onto 0.7-m^2 sheets of glass has been installed in Pacific Solar's pilot line. This equipment is identical in its basic design to a larger model that would be used to produce 1.4-m^2 CSG modules in a factory. Processes developed using this equipment in the pilot line can be confidently transferred to factory production. This equipment has been used to deposit large-area films that have excellent uniformity both in thickness and electrical performance. The best efficiency obtained for a module made using this material is currently 7.0% and is rapidly catching up with the 8.2% previously obtained with research-style equipment.

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REFERENCES

[1] Paul A. Basore and James M. Gee, 'Crystalline-Silicon Photovoltaics: Necessary and Sufficient', *24th IEEE Photovoltaic Specialists Conference* (1st WCPEC), Waikaloa, HI, Dec 1994, pp. 2254-2257.

[2] Paul A. Basore, 'Pilot Production of Thin-Film Crystalline Silicon on Glass Modules', *29th IEEE Photovoltaic Specialists Conf.*, New Orleans, May 2002, pp. 49-52.

[3] Paul A. Basore, 'Pilot Production of Thin-Film Crystalline Silicon on Glass Modules', *PV in Europe - From PV Technology to Energy Solutions*, Rome, Oct 2002, pp. 236-239.

[4] M.A. Green, K. Emery, D.L. King, S. Igari and W. Warta, 'Solar Cell Efficiency Tables (Version 21)', *Progress in Photovoltaics* **11** (1), Jan 2003, pp. 39-45.